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Emission abatement versus development as strategies to reduce vulnerability to climate change: an application of FUND

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ABSTRACT. Poorer countries are generally believed to be more vulnerable to climate change than richer countries because poorer countries are more exposed and have less adaptive capacity. This suggests that, in principle, there are two ways of reducing vulnerability to climate change: economic growth and greenhouse gas emission reduction. Using a complex climate change impact model, in which development is an important determinant of vulnerability, the hypothesis is tested whether development aid is more effective in reducing impacts than is emission abatement. The hypothesis is barely rejected for Asia but strongly accepted for Latin America and, particularly, Africa. The explanation for the difference is that development (aid) reduces vulnerabilities in some sectors (infectious diseases, water resources, agriculture) but increases vulnerabilities in others (cardiovascular diseases, energy consumption). However, climate change impacts are much higher in Latin America and Africa than in Asia, so that money spent on emission reduction for the sake of avoiding impacts in developing countries is better spent on vulnerability reduction in those countries.

His last big project in a long career, Jan Feenstra managed the Netherlands Climate Change Assistance Programme through which the Dutch Government sponsors climate change research in developing countries. He hated how climate change detracted from what he considered to be the real issues. This paper is dedicated to his memory.

1. Introduction

It is often noted that the level of (economic) development is one of the main determinants of vulnerability to climate change (e.g., Smith *et al.*, 2001). The

This paper benefited from discussions with Hadi Dowlatabadi and Tom Downing. Three anonymous referees made constructive comments. An earlier version of this paper was presented at the Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, on 10 April, 2002. The comments of the participants are greatly appreciated. The US National Science Foundation through the Center for Integrated Study of the Human Dimensions of Global Change (SBR-9521914) and the Michael Otto Foundation for Environmental Protection provided welcome financial support. All errors and opinions are mine.

reason is twofold. First, a larger share of the economy of poorer countries directly depends on weather and climate, for instance, in agriculture. Second, poorer countries have less means to defend themselves against the vagaries of the weather. As their exposure is higher, and adaptive capacity is lower, poorer countries are more vulnerable. Global climate change impact studies indeed confirm this, although one may wonder how much of this is 'assumption' and how much 'result'.

A corollary of 'poor is vulnerable' is that accelerating development is a strategy to reduce vulnerability to climate change, and – apart from the side benefits – perhaps a more effective one than reducing greenhouse gas emissions. This point is also noted with some regularity, most notably by Schelling (1992, 1995). However, to date, this is an assertion only. The relative strengths of development versus emission abatement in reducing vulnerability to climate change have yet to be quantified.

Tol and Dowlatabadi (2001) is an exception. However, that paper is limited to malaria only, and the argument is the other way around. Tol and Dowlatabadi use a model in which the incidence of malaria increases with global warming and decreases with economic growth. The model also includes international trade and investment, so that emission reduction in the OECD negatively affects growth in developing countries, particularly in Africa. They show that the economic growth forgone (in developing countries) because of ambitious emission reduction (in developed countries) would affect public health care, such that malaria actually increases, even though climate change is less.

This paper attempts a direct comparison between the two effects. It tests the Schelling Conjecture that money reserved for climate policy would be better spent on development. The paper estimates the marginal costs of climate change, and then estimates what would happen (at the margin) to the impacts of climate change if the same amount of money were invested in development rather than in emission abatement. Framed like this, we also avoid the tricky issue of estimating the impacts of emission reduction in the North on economic growth in the South (on which Tol and Dowlatabadi rely). Although the long-term effects are considered, the analysis is restricted to emissions and development aid in the current decade, so that policy conclusions hold only for the present and near future. As far as I know, this paper is the first attempt to do this.

A second difference between this paper and Tol and Dowlatabadi is that we here consider all impacts of climate change, rather than malaria only. Infectious diseases and development are *negatively* correlated: higher income is associated with lower incidence of diseases. However, other diseases, notably cardiovascular and respiratory disorders, are *positively* correlated to income (via diet and longevity). The issue is broader than health. Some vulnerabilities fall with income (e.g., agriculture), whereas others rise (e.g., energy consumption). Only if we include all impacts in a consistent way, can we genuinely investigate the trade-off between development and emission reduction as alternative means to reduce climate change vulnerability.

The literature on adaptation and mitigation strategies for climate change is thin. Most papers assume that one is a substitute for the other, without looking at the interactions between adaptation and mitigation (see the review by Toth *et al.*, 2001). One exception is Kane and Shogren (2000), who study the interactions from a risk perspective at a conceptual level, but without specifying these interactions. Another exception is Tol (2004), who focuses on the interactions in policy advice, rather than the interactions themselves.

A study like this is necessarily built upon a large number of assumptions.[1] These include scenarios of future developments, climate change, climate change impacts, and the relationship between vulnerability and development. These elements are all uncertain. Other assumptions are not just uncertain, but also controversial. These include how different impacts are aggregated, and how impacts are aggregated over nations and over time. Although the model used and the underlying assumptions are 'mainstream', and, although sensitivities are analysed, it is clear that this paper is only a first attempt at a complicated subject. The results indicate that further research in this area is worthwhile.

Section 2 presents the model used. Section 3 presents the scenarios and the results. Section 4 concludes.

2. The model

This paper uses version 2.4 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model.[2] Parts of the model go back to version 1.6 (see Tol, 1999a–e, 2002c). Other parts, particularly the impacts of climate change, go back to version 2.0 (Tol, 2002a,b). Relevant for this paper, compared with previous versions, version 2.4 has updated estimates of the impacts of climate change. See Smith *et al.* (2001) and Tol *et al.* (2001) for a discussion of the impacts of climate change.

Essentially, FUND consists of a set of exogenous scenarios and endogenous perturbations, specified for nine major world regions, namely OECD-America, OECD-Europe, OECD-Pacific, Central and Eastern Europe and the former Soviet Union, Middle East, Latin America, South and South-East Asia, Centrally Planned Asia, and Africa.

The model runs from 1950 to 2200, in time steps of a year. The prime reason for extending the simulation period into the past is the necessity to initialize the climate change impact module. In FUND, some climate change impacts are assumed to depend on the impact of the year before, so as to reflect the process of adaptation to climate change. Without a proper initialization, climate change impacts are thus misrepresented in the first decades. 'Scenarios' for the period 1950–1990 are based on historical observation, viz. the *IMAGE* 100-year database (Batjes and Goldewijk, 1994). The period 1990–2100 is based on the FUND scenario, which lies somewhere in between the IS92a and IS92f scenarios (Leggett *et al.*, 1992). Note that the original IPCC scenarios had to be adjusted to fit FUND's nine regions and yearly time-step. The period 2100–2200 is based on

[1] Unfortunately, the number of assumptions is so great that they cannot all be presented in full in a single paper.

[2] Model code and publications can be found at http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/fund.html

extrapolation of the population, economic, and technological trends in 2050–2100, combined with a gradual shift to a steady state of population, economy, and technology. The model and scenarios are so far extrapolated that the results for the period 2100–2200 are not to be relied upon. This period is only used to provide the forward-looking agents in FUND with a proper perspective.

The exogenous scenarios concern economic growth, population growth, urban population, autonomous energy efficiency improvements, decarbonization of the energy use, nitrous oxide emissions, and methane emissions.

Incomes and population are perturbed by the impact of climate change (Fankhauser and Tol, forthcoming). Population falls with climate change deaths, resulting from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to affect only the elderly, non-reproductive population; heat stress only affects urban population. Population also changes with climate-induced migration between the regions. Economic impacts of climate change are modelled as deadweight losses to disposable income, which in turn affect utility and investment. Scenarios are only slightly perturbed by climate change impacts, however, so that income and population are largely exogenous.

The endogenous parts of FUND consist of carbon dioxide emissions; the atmospheric concentrations of carbon dioxide, methane, and nitrous oxide; the global mean temperature; and the impact of climate change on coastal zones, agriculture, forestry, natural ecosystems, energy consumption, water resources, and human health.

Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. This is a simplified representation of the relevant atmospheric chemistry, but sufficient for our purposes. The carbon cycle is the five-box of Maier-Reimer and Hasselmann (1987), as used by Hammitt *et al*. (1992). Radiative forcing for carbon dioxide, methane, and nitrous oxide are based on Shine *et al*. (1990). The global mean temperature is governed by a geometric build-up to its equilibrium, with a life-time of 50 years. Global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Global mean sea level is also geometric, with its equilibrium determined by the temperature and a life time of 50 years. The model is calibrated to Kattenberg *et al*. (1996).

The climate impact module is fully described in Tol (2002a,b) and Tol and Heinzow (2003). The impact module has two units of measurement: people and money. People can die prematurely and migrate. These effects, like all other impacts, are monetized. Damage can be due to either the rate of change or the level of change. Benchmark estimates can be found in table 1. The benchmark estimates give the total welfare impact of a 1°C global warming on the current economy and population. The estimates are largely based on direct costs; e.g., wetland impacts are based on the average value of coastal wetlands times the total wetland area destroyed by sea level rise. Impacts are estimated independently of each other. Benchmark estimates as in Tol (2002a) are useful for model calibration, but not particularly insightful, as vulnerabilities change over time and climate change will not stop at a 1°C warming. Marginal cost estimates, discussed below, are more insightful.

Table 1. *Estimated impacts of a 1°C increase in the global mean temperature; positive numbers are gains, negative numbers are losses (Standard deviations are given in brackets)*

	Billion dollar		*Percent of GDP*	
OECD-A	184	(106)	3.60	(2.07)
OECD-E	212	(116)	3.89	(2.15)
OECD-P	38	(33)	1.20	(1.06)
CEE & fSU	60	(108)	2.10	(3.78)
ME	4	(8)	1.04	(2.15)
LA	−1	(5)	−0.15	(0.58)
S & SEA	−16	(9)	−1.90	(1.13)
CPA	9	(22)	2.00	(5.01)
AFR	−17	(9)	−4.10	(2.21)

Source: Tol (2002a); Tol and Heinzow (2003).

Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climate optimum. The climate optimum is determined by a mix of factors, including physiology and behaviour. Impacts are positive or negative, depending on whether climate is moving towards or away from that optimum climate. Impacts are larger if the initial climate is further away from the optimum climate. The optimum climate concerns the potential impacts. Actual impacts lag behind potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to the new climate are always negative. On the other hand, CO_2 fertilization positively influences agriculture. These impacts do depend on the initial climate in the region. See Tol (2002b) for the exact specification.

Other impacts of climate change, on coastal zones, forestry, unmanaged ecosystems, water resources, malaria, dengue fever, and schistosomiasis, are modelled as simple power functions. Impacts are either negative or positive, and do not change sign over time. These impacts are independent of the initial climate in the region, or implicitly depend on the initial climate through the calibration. See Tol (2002b) for the exact specification.

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as coastal zones (with population growth), heat-related disorders (with urbanization and an aging population, and with higher values from higher per capita incomes) and ecosystems (with higher income and loss of biodiversity, respectively). Other systems are projected to become less vulnerable, such as agriculture (with economic growth) and vector-borne diseases (with improved health care). Yet other systems become both more and less vulnerable, such as energy consumption and water resources (with technology and population growth). See Tol (2002b) for the exact specification.

The impact functions thus have the following shape, for impacts with an equilibrium

$$I_t = V(D_t)E(|T_t - T_{opt}|) + \rho I_{t-1}; \quad \frac{\partial E}{\partial X} > 0 \tag{1}$$

and for impacts without an equilibrium

$$I_t = V(D_t)E(T_t); \quad \forall t \frac{\partial E}{\partial T} > 0 \vee \frac{\partial E}{\partial T} < 0 \tag{2}$$

where I denotes impact, V denotes vulnerability as a function of development D, E denotes exposure as a function of the climate indicator(s) T, T_{opt} denotes the optimal climate, t denotes time, and ρ is a parameter. In (2), E is monotone in T. V is increasing in D for 'luxury' impacts (cardiovascular health problems, ecosystems) and decreasing for 'necessary' impacts (water resources, agriculture). Each sector has an impact function (1) or (2). Total impact sums over sectoral impacts; total impacts are thus highly non-linear in development and climate change.

The impact module of FUND2.4 is based on that of FUND2.0, fully described in Tol (2002a,b). The following changes were made, following the logic for updating impact estimates outlined in Tol (2002a). Morbidity was added by overlaying the changes in potential disease burdens (Marten *et al.*, 1997) with observed diseases patterns (Murray and Lopez, 1996); morbidity impacts are valued based on Navrud (2001). Vulnerability is modelled as for mortality. The effects of CO_2 fertilization and climate change on forestry and agriculture were separated, while parameters were updated with more studies (IEA GHG 1999; Sohngen *et al.*, 1996). The dynamics of water resources, energy consumption, and ecosystem impacts were made richer. Specifically, technological change was introduced in the water sector. The linear dependence of energy consumption on climate was replaced by a more realistic non-linear representation, reflection saturation of demand. Biodiversity loss is now assumed to lead to an increase in the value of the remaining species, using the specification of Weitzman (1998). See Tol and Heinzow (2003) for an extensive description of the new model; note that the marginal impact estimates of greenhouse gas emissions are not much affected by these changes in the model.

3. Abatement versus development

Table 2 shows the difference in the net present value of climate change impacts due to a small change in carbon dioxide emissions[3] in the period 2000–2009, normalized by that emissions change. That is, table 2 shows the marginal damage costs of carbon dioxide emissions, also known as the social costs of carbon; the marginal damage costs equal the Pigou tax. Table 2 also shows the regional distribution of the marginal damage costs.[4] Western Europe, particularly its health and energy consumption, is the

[3] 1 million tonnes of carbon per year, while total emissions are 6 billion tonnes of carbon per year.

[4] Note that the regional distribution of total costs (table 1) and the regional distribution of marginal costs (table 2) do not match, at least not at first sight. This is because, in FUND, climate change impacts are specified per sector as well as per region. Each region and each sector has different development scenarios. Although this obscures the estimates of marginal costs of carbon dioxide emissions, this feature of the model does allow for estimating the effect of development on climate change impacts.

Table 2. *Regional marginal costs of CO_2 emissions and marginal benefits of development aid on climate change impacts in the period 2000–2009*

	Marginal costs of CO_2 emissions[a]			*Marginal benefits of development aid*[b]			*Cost–benefit ratio*[c]		
PRTP[d]	0%	1%	3%	0%	1%	3%	0%	1%	3%
OECD-A	4.04	−0.39	−3.15						
OECD-E	9.07	4.10	0.40						
OECD-P	−4.33	−5.01	−4.39						
CEE & fSU	7.65	3.41	0.31						
ME	−0.09	−0.15	−0.13						
LA	1.10	0.66	0.25	0.05	0.08	0.06	0.9	2.3	5.2
S & SEA	0.03	−0.03	−0.06	−0.17	−0.08	−0.02	−99.9	63.9	8.1
CPA	0.01	−0.28	−0.42	−0.65	−0.41	−0.20	−1465.1	29.1	0.0
AFR	2.44	1.46	0.60	3.08	1.75	0.63	25.3	23.9	20.8
Sum	19.93	3.77	−6.59						
EqW	16.13	6.59	−0.50						

Notes: [a] Positive numbers are marginal costs, negative numbers are marginal benefits of carbon dioxide emissions.
[b] Positive numbers are marginal benefits, negative numbers are marginal costs of development aid; only the effects of aid on climate change impacts are included.
[c] 20 × ‘marginal benefits of development aid’/‘marginal costs of CO_2 emissions’.
[d] PRTP = pure rate of time preference, or utility discount rate.
Source: Own calculations.

most vulnerable of the OECD regions; the other parts of the OECD even substantially benefit from climate change in the short run, mostly because of reductions in cold-related mortality and morbidity. The countries of Central and Eastern Europe and the former Soviet Union suffer from climate change, particularly with regard to water resources. South and Southeast Asia and China also benefit from climate change, particularly in agriculture and energy. However, Latin America and Africa are, on balance, negatively affected, with water resources, energy consumption, and health being the main contributors to the overall damage.

Table 2 also shows the marginal costs of carbon dioxide emissions for the whole world, using both a simple addition of dollar values and so-called equity weights (Fankhauser *et al.*, 1997, 1998), through which monetary losses are corrected for their impact on utility. As the effects of current carbon dioxide emissions will only be felt in the future, the marginal damage costs strongly depend on the discount rate; note that table 2 specifies the utility discount rate, or pure rate of time preference.

Speeding up development may help or hinder vulnerability to climate change. Table 2 shows by how much, again for development aid spent in the period 2000–2009.[5] The marginal benefits of development aid are defined

[5] The effect of development aid is to permanently increase per capita income, by increasing productivity. In the base specification, one dollar spent on development

to resemble the marginal damage costs: if a little more aid would be given, how much would climate change impacts fall? The marginal benefits of development aid are the difference in the net present value of the impacts, normalized by the change in development aid.

In Asia, faster development increases vulnerability, because agriculture becomes less important – climate change affects agriculture positively – and because heat-related cardiovascular and respiratory disorders are more prominent in wealthier societies. In Latin America, the health balance is more towards poverty-related (i.e., vector-borne, infectious) diseases and cold-related cardiovascular disorders, so that faster development reduces vulnerability. However, the return on such investments is small: for every dollar invested, 5–8 cents worth of avoided impacts is gained. In Africa, investing in development does pay off, at least for low discount rates. With a pure rate of time preference of 1 per cent (0 per cent), every invested dollar yields a return of 175 per cent (308 per cent). For higher discount rates, the investment is not worthwhile: an invested dollar returns 63 cents if the pure rate of time preference equals 3 per cent.[6] The climate-related benefits of faster development in Africa are dominated by human health, with energy consumption a distant second.

The marginal costs of carbon dioxide emissions and the returns to investment in development are readily compared. If climate policy is very modest and the marginal costs of emission reduction are only \$1/tC, one can directly compare the marginal costs of carbon dioxide emissions to the returns to investment given in table 2. A dollar invested in emission reduction is worth less than a dollar invested in development for Africa only; this is regardless of the discount rate, although the effect is more pronounced for lower discount rates. Latin America would rather see the dollar invested in emission reduction (for all three discount rates, but this preference is less strong for higher discount rates), whereas Asia would rather see the dollar not invested in climate policy, except if the discount rate is very low, in which case emission reduction would benefit Asia.

If climate policy is more ambitious, running at marginal abatement costs of \$20/tC (more or less Kyoto; Buchner *et al.*, 2002), then the returns of investment should be multiplied by 20 before they can be compared with the marginal costs of carbon dioxide emissions. Table 2 shows the results ('cost–benefit ratio'). Africa and, for a sufficiently high discount rate, Latin America would benefit more, in climate change impact terms, from a dollar invested in development than from a dollar invested in emission reduction. Asia would rather not see any such investment, but a dollar invested in emission reduction does less harm than a dollar invested in development.

aid leads to a 5 cents increase in GDP in the beneficiary country. Easterly (2002), among many others, makes it clear that this specification is simplistic, without offering a more realistic, generic relationship between aid and development.

[6] Although consumption discount rates are generally higher in developing countries than in developed countries, there is no a priori reason to assume the same would hold for the utility discount rate or pure rate of time preference. A pure rate of time preference of 3 per cent seems to describe economic behaviour best (Arrow *et al.*, 1996).

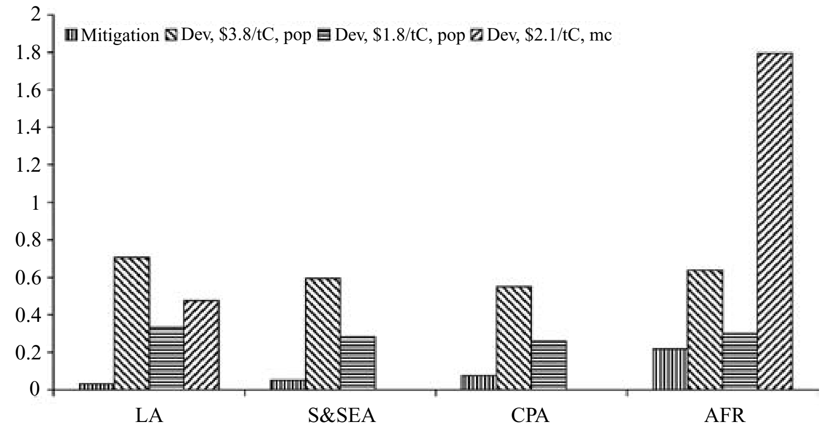

Figure 1. *The net present welfare gains (discounted to 2000 at 1 per cent a year) of 10 million metric tonnes of emission reduction between 2000 and 2009, and an additional transfer of 38, 18, and 21 million US dollar between 2000 and 2009 to four developing regions, distributed proportional to population (pop) or regional marginal costs of carbon dioxide emissions (mc)*

If, however, a dollar invested in development only brings 5 cents worth of growth stimulus, then one should multiply the cost–benefit ratio in table 2 by 0.05; that is, directly compare the marginal costs of emission reduction with the marginal benefits of development aid (see previous paragraph).[7]

Of the four developing regions, Africa is the largest contributor to the worldwide marginal impacts of climate change. South and Southeast Asia and China have positive, but small marginal impacts, while Latin America's marginal impacts are intermediate and negative. Any investment in greenhouse gas emission reduction on behalf of the developing countries is thus to a large extent on behalf of Africa. Africa, however, would rather see the money invested in development, even from the narrow perspective of reducing climate change impacts.

Figure 1 shows the effects on net present welfare (not just associated with climate change impacts) of a arbitrary but small emission reduction of 10 million tonnes of carbon[8] and three 'equivalent' transfers of development aid. In the first transfer, emission reduction is assumed to cost \$3.8/tC[9], and \$38 million in development aid is distributed proportional to population.

[7] The interpretation of a \$20/tC emission abatement policy and 5 per cent effective development aid is maintained below. Readers who prefer more or less stringent emission abatement or more or less effective development aid should multiply the ratios reported below with the appropriate factor.

[8] About 0.03 per cent of OECD emissions.

[9] The Pigouvian tax, that is, the global marginal costs of carbon dioxide emissions at a 1 per cent pure rate of time preference. Note that it is not implied that OECD emissions would fall by 10 million tC if a tax of \$3.8/tC is levied; the carbon price is defensible from a welfare perspective, while the 10 million tC signify just a small variation around the baseline.

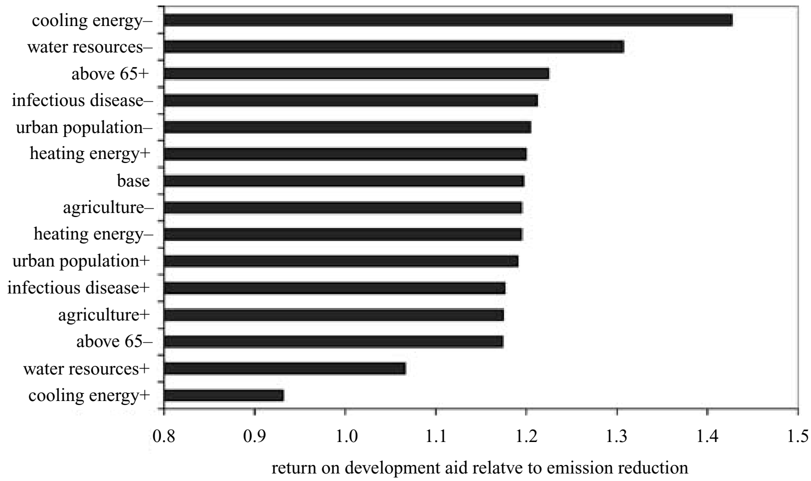

Figure 2. *The return on development aid in Africa relative to emission reduction (for a climate policy costing* $20/tC *and a 5 per cent effective development aid) as a function of the parameters that govern the sensitivity of climate change impacts to economic development*

In the second transfer, only $18 million[10] is given in development aid. In the third transfer, $21 million[11] is given in development, this time distributed proportional to the regional marginal costs. Each of the four developing regions clearly prefers to receive aid rather than see greenhouse gas emissions reduced.

The figures in table 2 are very uncertain. A large number of assumptions underlie these estimates, including future developments, the climate sensitivity, the sensitivity of society to climate change, and the sensitivity of vulnerability to development. Agriculture, water resources, energy consumption, and human health are the most important impacts for developing countries. Figure 2 displays a sensitivity analysis around the parameters that govern the sensitivity of these sectors to development. These parameters are the per capita income elasticity of the demand for energy, water, and agriculture, and the relationship between wealth, on the one hand, and age structure, urbanization, and infectious diseases, on the other. These seven parameters are varied with one standard deviation from the mean. The return to development aid for Africa relative to the return to emission reduction for a $20/tC emission abatement policy and a 5 per cent effective development aid is not very sensitive to these parameters, except for the expansion of water demand with economic growth and the rate of penetration of air conditioning. Even then, the return on aid varies not more than 25 per cent from the base value. For a $20/tC emission reduction policy, 5 per cent effective aid, and a rapid penetration of air conditioning, Africa would prefer investment in emission abatement to investment in

[10] $1.8/tC is the marginal damage cost to the developing regions.
[11] $2.1/tC is the marginal damage cost to Africa and Latin America.

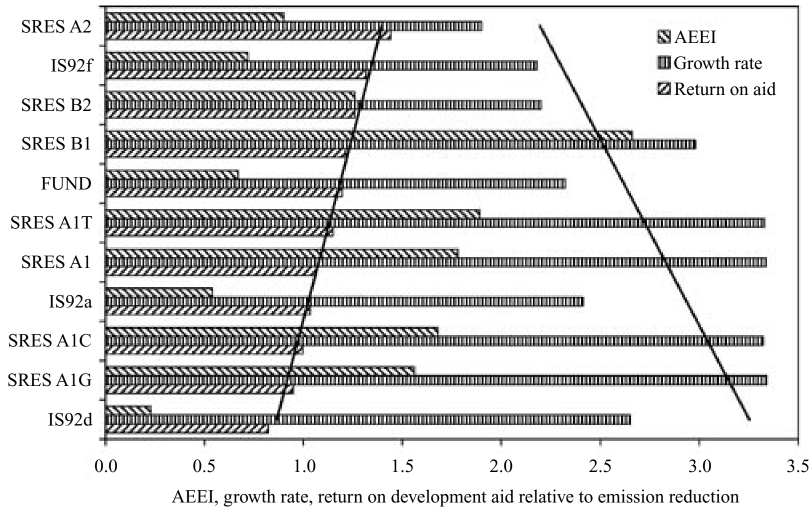

Figure 3. *The return on development aid in Africa relative to emission reduction (for a climate policy costing $20/tC and a 5 per cent effective development aid) as a function of the baseline scenario; also shown is the assumed average growth rate of per capita income in Africa in the twenty-first century and the Autonomous Energy Efficiency Improvement (AEEI)*

development aid; for all other sensitivity analyses, and for more ambitious emission reduction policy, the reverse would be true. Other regions have similar sensitivities (results not shown). For other discount rates, the picture is similar too (results not shown).

Figure 3 displays the sensitivity to the baseline scenario of the return on development aid relative to emission abatement, for Africa, for a $20/tC emission reduction policy, 5 per cent effective aid, and a 1 per cent pure rate of time preference. Results are presented for 11 scenarios. The FUND scenario is the basis. Three older IPCC scenarios are used, viz. IS92a (business as usual), IS92d (low emissions), and IS92f (high emissions); see Leggett *et al*. (1992). The four newer IPCC scenarios are also used, viz. A1, A2, B1, and B2 with three variants on A1 namely A1C, A1G, and A1T; see Nakicenovic and Swart (2001). The return on development aid relative to emission reduction ranges from 0.82 to 1.44 for an emission abatement policy of $20/tC and 5 per cent effective aid: Only under IS92d and SRES A1G does Africa prefer investments in emission reduction over investments in development aid; for more ambitious emission reduction policies, Africa always prefers development aid. The differences in outcome between the scenarios can be to some extent explained from the differences in the assumed growth rates of per capita income, also displayed in figure 3. Development pays less than does emission reduction if the economic growth rate is high. The intuition behind this scenario dependence is clear, and the same as that behind the differences between the developing regions. Development aid helps the least developed the most. However, the assumed rate of technological progress matters as well. Figure 3 also shows the

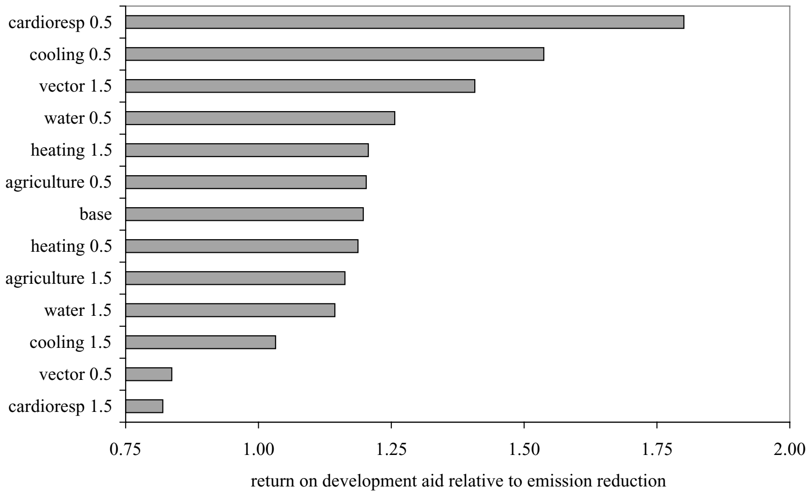

Figure 4. *The return on development aid in Africa relative to emission reduction (for a climate policy costing $20/tC and a 5 per cent effective development aid) as a function of the severity of selected climate change impacts*

average AEEI in Africa in the twenty-first century; a low AEEI has the opposite effect of a high growth rate. With a high AEEI, the costs of air conditioning fall, and the impacts of climate change become less sensitive to the growth rate of the economy (cf. figure 2). The picture is similar for other climate policies, regions, and discount rates (results not shown).

Figure 4 shows the results of a sensitivity analysis on the impacts of climate change in Africa, again focussing on a $20/tC emission reduction policy, a 5 per cent effective development aid policy, and using a pure rate of time preference of 1 per cent. The effects on energy consumption, water resources, agriculture, vector-borne diseases, and cardiovascular and respiratory mortality and morbidity are increased and decreased by 50 per cent. The return on development aid in Africa is least sensitive to the assumed impact on heating energy and agriculture, followed by water resources, cooling energy, vector-borne diseases, and cardiovascular and respiratory disorders. The return on development aid falls below one only if vector-borne diseases increases much less with climate change than expected, or if cardiovascular and respiratory diseases increase much more. With less vector-borne diseases, the impacts of climate change become less sensitive to development. This is reverse for cardiovascular disorder because the dynamics of cold-related deaths dominate in the short run, also in Africa. The picture is similar for other climate policies, regions, and discount rates (results not shown).

4. Discussion and conclusion

The above analysis shows that, for the period 2000–2009, investing in development, particularly in the poorest countries, may well be a better strategy for reducing the impacts of climate change than is greenhouse gas emission reduction.[12] This conclusion is in line with the findings of Tol and Dowlatabadi (2001), the only other paper on this subject. Regional comparisons and sensitivity analyses shows that this is particularly the case if development aid targets vector-borne infectious diseases and water resources; the result does not vary much with the discount rate. With generic development aid, the gains in water resources and infectious diseases would be partly offset by increases in energy consumption for cooling and cardiovascular diseases. The policy conclusion would be that money spent on reducing exposure (greenhouse gas emissions) for the sake of poverty-related climate change impacts is better spent on alleviating those vulnerabilities directly.

This paper does not address the trade-off between environmental protection and development in general, or even between emission reduction and development aid. The paper is restricted to comparing two strategies to reduce the impact of climate change. Broader questions are obviously important, but would require a more extensive model than the current version of FUND. The conclusions are also restricted to policies in the current decade; the results of the current model may well be different for later periods, so that analyses like these should be repeated with up-to-date knowledge.

The conclusions drawn from this paper should be treated with caution. After all, despite the extensive sensitivity analyses, the findings are based on one single model. Given the importance of vector-borne diseases and water resources in the results, the results should be further investigated with more detailed models of these sectors, and more detailed models of the delivery of foreign aid.

Other authors (Cline, 1992; Fankhauser, 1995; Mendelsohn *et al.*, 2000; Nordhaus, 1994) have estimated other climate change impacts per region and per sector; this would lead to different results, at least quantitatively but perhaps also qualitatively. These studies, however, have a less dynamic specification of the relationship between development and vulnerability, and therefore do not readily lend themselves to analyses as in this paper.

This paper puts spending on greenhouse gas emission reduction in a broader context, and demonstrates that that may change the conclusions. In a narrow sense, cutting greenhouse gas emissions helps alleviating malaria and water shortage. In a broader sense, the same money can be spent differently to alleviate climate-change-induced malaria and water shortage even more. Only by considering the broader question can we decide how much effort should be expended on greenhouse gas emission abatement.

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[12] The paper also shows that, if the purpose of climate policy is to improve the welfare of the poor, the money reserved for emission abatement is better given to them directly; this finding is trivial.

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